Introduction

The selection of the best protection devices and transformer designs are excellent ways to reduce arc flash hazards. It is the intent of this paper to address various examples of common transformer protection methods and examine the effect each has on the arc flash category and hence the PPE that would be required to keep any injuries to a minimum.

Background

Although Arc Flash Hazards have been present for over a century, it has received significant attention in the past few years, stemming from the 2007 revision of the National Electric and Safety Code (NESC). The 2007 revision of the NESC, Rule 410A3 states:

“Effective January 1, 2009, the employer shall ensure that an assessment is performed to determine potential exposure to an electric arc for employees who work on or near energized parts or equipment. If the assessment determines a potential employee exposure greater than 2 cal/cm² exists, the employer shall require the employee to wear clothing or a clothing system that has an effective rating at least equal to the anticipated level of arc energy.”

What is Arc Flash?

Arc Flash is defined by the National Fire Protection Association as “a dangerous condition associated with the release of energy caused by an electrical arc.” An Arc Flash is basically an electrical short circuit through the air. During an Arc Flash incident, concentrated radiant energy explodes outward, releasing a superheated ball of gas and shrapnel with a temperature of possibly four times that of the sun. In addition there is a tremendous blast force, blinding UV light and a loud noise.

Arc Flash Categories

Arc Flash has been categorized by the amount of heat generated at a distance of 18” from the source of the arc. The primary protection used to reduce the effect of arc flash on personnel, is the use of proper Personal Protective Equipment, commonly known as “PPE.”
The Arc Flash categories, the heat generated and the PPE required by NESC for each category is listed in the following chart:

<table>
<thead>
<tr>
<th>Category</th>
<th>Heat Generated</th>
<th>PPE Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( \leq 2 \text{ cal/cm}^2 )</td>
<td>Long sleeve shirt&lt;br&gt;Long pants&lt;br&gt;Safety Glasses&lt;br&gt;Non-melting untreated natural fiber</td>
</tr>
<tr>
<td>1</td>
<td>( \leq 4 \text{ cal/cm}^2 )</td>
<td>FR long sleeve shirt&lt;br&gt;FR pants with a minimum arc rating of 4&lt;br&gt;or&lt;br&gt;Long pants - untreated denim cotton blue jeans of 12oz/yd²&lt;br&gt;or&lt;br&gt;FR coveralls - arc rating of 4 instead of FR shirt and pants&lt;br&gt;Hard Hat</td>
</tr>
<tr>
<td>2</td>
<td>( \leq 8 \text{ cal/cm}^2 )</td>
<td>In addition to items listed in Category 1, use&lt;br&gt;Face shield with a minimum arc rating of 8&lt;br&gt;Wrap-around guarding for forehead, ears and neck&lt;br&gt;Could use flash hood suit</td>
</tr>
<tr>
<td>3</td>
<td>( \leq 25 \text{ cal/cm}^2 )</td>
<td>Cotton undergarments&lt;br&gt;Non-melting long sleeve shirt and pants&lt;br&gt;FR shirt and pants&lt;br&gt;FR coveralls&lt;br&gt;Hearing protection&lt;br&gt;Safety glasses or goggles&lt;br&gt;Hand protection&lt;br&gt;Foot protection</td>
</tr>
<tr>
<td>4</td>
<td>( \leq 40 \text{ cal/cm}^2 )</td>
<td>Cotton shirt and pants&lt;br&gt;FR shirt and pants&lt;br&gt;Flash suit and hood&lt;br&gt;Hearing protection&lt;br&gt;Safety glasses&lt;br&gt;Hand protection&lt;br&gt;Foot protection</td>
</tr>
<tr>
<td>Dangerous</td>
<td>&gt; 40 cal/cm²</td>
<td>No safe protection</td>
</tr>
</tbody>
</table>

It should be noted that 1.2 cal/cm² is the threshold of a second degree burn. Arc flash protection is designed to limit the injury to no more than a “just curable” 2nd degree burn. You can still be burned by abiding by the rules.

As a reference:
- 1st degree burns affect the outer layer of skin, it is painful, but not usually permanent or life threatening
- 2nd degree burns cause tissue damage and blistering. The outer skin layer is destroyed.
- 3rd degree burns cause the complete destruction of skin. Small areas may recover, large areas will need skin grafting.

**How are Arc Flash Calculations Made?**

The conditions that determine the amount of Arc Flash and the resultant heat, etc. depend upon the following:

1. The fault current available at the arc, which is based on the impedance of the system at the arc. The higher the impedance, the less the fault current available.
2. The time duration of the arc, determined by the back-up protection that operates, interrupting the power to the arc.
3. The surrounding environment of the arc, related to whether the arc occurs in “open air” or in a “box”. An arc in open air is not as confined and allows the energy to be dissipated in many directions. An arc in a box focuses the energy, pressure, debris, etc. in one direction – toward the worker. Hence, arcs in open air are less damaging as those in a box.

There are two methods of Arc Flash Calculations:

IEEE 1584-2002
NFPA 70E - 2004, Annex D

Both methods of calculation are commonly used, but the following discussion uses the IEEE 1584 method. It should be noted that this paper is not all encompassing and only shows a few typical examples. The user must still comply with all of the requirements of these standards which contain additional details for formulas for other voltages and for consideration of current limitation not shown here.
The formulas for the calculations will not be discussed here, as the details can be found in IEEE 1584-2002, but the results from using the formulas on various protection methods will be discussed.

**What can be done to reduce Arc Flash Hazards?**

1. **Wear the proper Personal Protective Equipment**
   
   Wearing the proper PPE is vital to the protection of the person operating the equipment. However, it is not the intent of this paper to address the details of PPE.

2. **Minimize the Fault Current Available**
   
   In most instances, there is little that can be done on an existing system to reduce the fault current available. The magnitude of an arcing fault will be less than a bolted fault, due to the arc impedance and arc gap distance. Although the arc gap distance may vary, a gap of 1” (25mm) is used in the following calculations.

3. **Minimize the Time Duration of the Arc**
   
   The time duration of an arc is dependent upon the protection devices that are used to clear the fault. The characteristics of protection devices are typically expressed in Time-Current Curves (TCC). At a given fault current level, the time to clear the fault can be easily determined using the TCC’s. Since protection devices have their own unique TCC’s, the time duration of the arc may be reduced by the proper selection of protective equipment. The TCC’s are available from the transformer manufacturer and the protective equipment manufacturer.

4. **Change the surrounding environment of the arc**
   
   There is not much that can be done with existing equipment to change the environment around a potential arc.

   Pole mounted transformers (both 1Ø and 3Ø) are considered “Open Air” applications, which have the least arc flash consequences. However, both primary and secondary conductors are exposed to arc flash hazards.

   Pad mounted transformers are considered to be “Box” which exhibit the worst arc flash situations. A “Box” is defined as an 18” box with a back, a top and two sides. The front is open. Unfortunately, the open front is always towards the person most likely to be injured by an arc flash. Most pad mounted transformers have separable insulated high voltage connectors. The insulated primary help reduce the risk of arc flash on the primary side. However, the secondary of the transformers are frequently uninsulated, causing a much greater arc flash risk.

   Although single-phase pad mounted transformers with flip-top doors are considered to be a box, they do offer some degree of openness allowing the arc to dissipate in three additional directions (upward, left and right). However, there are no factors in the formulas which take this into consideration when calculating arc flash.

   Three-phase pad transformers are somewhat different, in that most designs are more truly a “box”. Typically, there is a cabinet containing both primary and secondary conductors, each having an access door. The primary door may only be opened after the secondary door is opened, but as stated earlier, the dead front construction used in most pad mounted transformers, minimizes the arc flash risk on the primary side. However, when the secondary door is opened, it exposes uninsulated conductors causing an arc flash risk. The secondary side of most 3Ø pad designs are box-like, consisting of a left-hand partition separating the low voltage from the high voltage compartments, a top covering the compartment, and a right-hand side. Only the front is open, exposing the operator to possible arc flash hazards. One manufacturer has a swing open top and side doors, resulting in a one-sided box. This reduces the arc flash hazard, since there are more directions the arc flash can be dispersed.

   Changes in the environment may be in the form of one or more of the following:
   - Use insulating boots over any exposed live parts
   - Specify transformer designs that allow for removing adjacent ground planes such as side doors and tops
   - Specify transformer designs that have rounded corners to reduce the possibility of catching and tearing PPE
   - Specify additional clearance between and around LV bushings (non-IEEE Standard)
Transformer Protective Devices Evaluated

1Ø Pole Transformers
- Secondary Circuit Breaker (evaluated)
- Primary Switch (evaluated)

1Ø and 3Ø Pad Mounted Transformers
- Primary Bayonet Fuse (evaluated)
- Primary CL Fuse (dry well evaluated)
- Primary Switch (evaluated)
- Secondary Circuit Breaker (evaluated)

For personnel safety, the worst case scenario was assumed. Therefore, evaluation assumed an infinite buss and the clearing time for the protective equipment was based on the Maximum Total Clear TCC's.

Details and Results of the Evaluation

1. 1Ø Pole Transformers
   Two methods of protection were evaluated, LV circuit breakers and HV switches at impedances of 1.5%, 2.0% and 2.5% (See Table 1). The study is based on a primary voltage of 12470GrdY/7200 and a secondary voltage of 120/240.
   a. LV circuit breakers provided the maximum amount of protection in nearly all cases (up thru 100 kVA), using the “Open Air” or “Box” calculations. The heat generated from an arc fault was nearly always less than 2 cal/cm² (PPE Category 0).
   b. The HV switches provided less protection and from 25 and 37.5 kVA, required Category 1 PPE and Category 2, 3 or 4 PPE is required for 50 kVA and higher using the “Open Air” calculations. When calculated in a “Box”, even less protection was given, resulting in the need for Category 2, 3 or 4 PPE starting at 25 kVA. The HV switches actually exceeded the Category 4 PPE on 2.5% impedance 167 kVA's when calculated in a “Box”.

2. 1Ø Pad Transformers
   Six methods of protection were evaluated; bayonet fusing (dual sensing, dual element and current sensing), LV circuit breakers, HV switches and full range CL fuses in dry well canisters. Each method was evaluated at impedance levels of 1.5%, 2.0% and 2.5% (See Table 2). The study is based on a primary voltage of 12470GrdY/7200 and a secondary voltage of 240/120.
   a. LV circuit breakers provided the maximum amount of protection in nearly all cases (up thru 100 kVA), using the “Open Air” or “Box” calculations. The heat generated from an arc fault was nearly always less than 2 cal/cm² (PPE Category 0). The 167 kVA's needs Category 0 thru 4 PPE, depending upon impedance and “Open Air” or “Box” calculations.
   b. The bayonet fusing yielded slightly differing results, depending upon the type of fuse element used. The current sensing fuses offered the best protection, but still required Category 1 or higher PPE. The dual sensing and dual element fuses less protection and required Category 1 or higher PPE starting at 25 kVA and up, depending upon impedance. The dual element fuses actually exceeded the Category 4 PPE on high impedance 75 kVA's and on 167 kVA's.
   c. The full range CL fuses in dry well canisters, provided some protection using both “Open Air” as only Category 1 PPE is required up thru 75 kVA. Using the “Box” calculations, Category 1 or 2 PPE is required up thru 75 kVA. The full range CL fuses in dry well canisters exceeded the Category 4 PPE 167 kVA's when calculated in a “Box”.
   d. The HV switches provided less protection and from 25 and 37.5 kVA, required Category 1 PPE and Category 2, 3 or 4 PPE is required for 50 kVA and higher using the “Open Air” calculations. When calculated in a “Box”, even less protection was given, resulting in the need for Category 2, 3 or 4 PPE starting at 25 kVA. The HV switches actually exceeded the Category 4 PPE on 2.5% impedance 167 kVA's when calculated in a “Box”.

3. 3Ø Pad Transformers
   Six methods of protection were evaluated; bayonet fusing (dual sensing, dual element and current sensing), LV circuit breakers, HV switches and full range CL fuses in dry well canisters. Each method was evaluated at the minimum and maximum impedance levels defined by IEEE C57.12.34-2004 and from 75-500 kVA, where a range is allowed an impedance of 2.0% was included (See Table 3). The study is based on a primary voltage of 12470GrdY/7200 and a secondary voltage of 208Y/120.
a. None of the bayonet fusing schemes yielded good results, however, there were slightly varying results, depending upon the type of fuse element used. Both the dual sensing and dual element fuses offered the least amount of protection, requiring Category 1 thru 4 PPE depending upon kVA and impedance with some exceeding Category 4 PPE starting at 112.5 kVA and should be considered very dangerous. The current sensing fuses offer slightly better protection requiring Category 1 thru 4 PPE up thru 300 kVA. However, on some 225 kVA’s and also 300 kVA and higher, the arc flash exceeded Category 4 PPE and should be considered very dangerous.

b. LV circuit breakers offered better protection in certain circumstances such as low impedance 112.5 kVA and 150 kVA. High impedances of 5.75% on 112.5 and 150 kVA, actually exceeded Category 4 PPE and should be considered very dangerous. It should be noted that LV circuit breakers are not offered above 150 kVA.

c. The full range CL fuses in dry well canisters did not offer any better protection than current sensing bayonet fuses, requiring Category 2 thru 4 PPE up thru 225 kVA. On 500 kVA and higher, the arc flash exceeded Category 4 PPE and should be considered very dangerous.

d. The HV switches did not offer any better protection than the bayonet fuses. The higher impedances of 5.75% actually can develop arc flash exceeding Category 4 PPE on 150 thru 500 kVA, which should be considered very dangerous. It should be noted that HV switches are not offered above 500 kVA.

Summary

1. 1Ø Pole Mounted Transformers

   While there were only two devices studied, the LV breaker and the HV switch, it is clear that the LV circuit breakers offered the maximum degree of protection.

2. 1Ø Pad Mounted Transformers

   Of the six methods of protection studied, five performed quite similarly, and were not nearly as good as the sixth method. The LV circuit breaker clearly outperformed all other methods of protection. Only high impedance 15 and 25 kVA’s require Category 1 PPE, and the 167 kVA’s require Category 1 thru 4, depending upon impedance. All other combinations of kVA and impedance do not require extra levels of PPE above the standard Category 0 PPE using the LV circuit breaker. All other protection methods, the three bayonet fuse types, the HV switch and the full range CL fuse in dry well canisters performed similarly, with the current sensing bayonet being the second best following the LV circuit breaker. Clearly, the LV circuit breakers offered the maximum degree of protection of all 1Ø devices investigated.

3. 3Ø Pad Mounted Transformers

   While there are no clear cut choices that provide the best protection, the two best are the current sensing bayonet and the full range CL fuse in dry well canisters. In virtually all of the applications examined, there were nearly none that do not require extraordinary PPE. Both the LV breakers and HV switches have application limitations. The LV breaker is only offered up thru 150 kVA and requires additional PPE for high impedances. The HV switch is only offered up thru 500 kVA and requires additional PPE for all applications.

4. General Observations

   In conducting this study, there was an interesting surprise. Conventional wisdom suggests that a higher impedance is better because it limits the fault current (ignoring the poorer voltage regulation). However, when calculating Arc Flash, higher impedances are actually poorer. This is due to the lower fault currents taking considerably longer to operate any protection equipment. Short time is much more helpful than lower current. It should be noted that partial range current limiting fuses were not evaluated because they must be coordinated with some type of weak link fuse. Proper selection of the partial range current limiting fuse is based on the crossover point being above the maximum secondary fault current of the transformer. Therefore, the partial range current limiting fuse would never operate and clear an arc flash event, and only protection would be the weak link fuse.
Conclusions

1. Arc Flash can happen in an “instant”. An interesting analogy is the speed of arc flash related to a common automobile airbag deployment. A chart describing the sequence of events during arc flash as related to an airbag deployment is attached.

2. Proper PPE is needed to limit the burns to 1st degree, during arc flash.

3. Some common transformer protective equipment allows excessive arc flash that exceeds any PPE ratings and should be considered very dangerous.

4. On 1Ø transformers, one protection method clearly offers the least amount of arc flash and hence the maximum degree of personnel safety.

5. On 3Ø transformers, there is no clear protection method that offers improved arc flash protection. Transformer designs featuring open sides and covers allow the arc flash to dissipate in more directions, intuitively reducing the arc flash effect on nearby personnel. In addition, rounded corners on exposed sheet metal can reduce the risk of catching and tearing personal protective equipment. Also, the use of insulating boots and specifying additional clearances could aid in providing a safer environment.
Table 1
1Ø Poles Arc Flash Summary
7200V Primary - 240/120V Secondary 1 inch conductor gap 18 in working distance

<table>
<thead>
<tr>
<th>kVA</th>
<th>IZ</th>
<th>Breaker</th>
<th>Low Voltage Circuit Breaker</th>
<th>HV Magnex Switch</th>
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<tbody>
<tr>
<td></td>
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<td>PPE Category</td>
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* With magnetic trip feature

---

**PPE Categories**

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<th>Code</th>
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### Table 2

1Ø Pads Arc Flash Summary

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<th>Fuse</th>
<th>PPE Category</th>
<th>Dual Sensing Bayonet Fuse</th>
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<th>PPE Category</th>
<th>Current Sensing Bayonet Fuse</th>
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<th>Low Voltage Circuit Breaker</th>
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<th>HV Magnex Switch</th>
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<th>Dry Well Canister (ELX CL Fuse)</th>
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### PPE Categories

- < 2 cal/cm²: 0
- 2 - 4 cal/cm²: 1
- 4 - 8 cal/cm²: 2
- 8 - 25 cal/cm²: 3
- 25 - 40 cal/cm²: 4
- > 40 cal/cm²: Dangerous
### Table 3
3Ø Pads Arc Flash Summary

<table>
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<tr>
<th>kVA</th>
<th>IZ</th>
<th>Dual Sensing Bayonet Fuse</th>
<th>Dual Element Bayonet Fuse</th>
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### PPE Categories
- **< 2 cal/cm²**: 0
- **2 - 4 cal/cm²**: 1
- **4 - 8 cal/cm²**: 2
- **8 - 25 cal/cm²**: 3
- **25 - 40 cal/cm²**: 4
- **> 40 cal/cm²**: Dangerous
Calculation Steps from IEEE 1584-2002

Step 1  Estimation of the Arcing Short Circuit Current

\[
\log I_a = k + 0.662 \times \log I_{bf} + 0.0966 \times V + 0.000526 \times G + 0.5588 \times V \times \log I_{bf} - 0.00304 \times G \times \log I_{bf}
\]

\[I_a = 10^{\log I_a}\]

Where,
- \(I_a\) = arcing current in kA
- \(k = -0.153\) for open air and \(-0.097\) for arcs in a box
- \(I_{bf}\) = bolted three-phase available short circuit current (symmetrical rms kA)
- \(V\) = system voltage in kV
- \(G\) = conductor gap in millimeters (mm)

Step 2  Calculation of the Normalized Incident Energy at Working Distance

\[
\log E_n = k_1 + k_2 + [1.081 \times (\log I_a)] + 0.0011 \times G
\]

\[E_n = 10^{\log E_n}\]

Where,
- \(E_n\) is the normalized incident energy (Joules/cm²), at the worker location for 24" (610mm) gap and 0.2 seconds
- \(k_1\) = open air or in a box factor (-0.792 or -0.555, respectively)
- \(k_2\) = grounded or ungrounded factor (-0.113 or 0, respectively)
- \(I_a\) = arcing current in kA (from Step 1)
- \(G\) = conductor gap in millimeters (mm)

Step 3  Calculation of the Incident Energy at Other Working Distances and Other Fault Clearing Times

\[
E = 4.184 \times C_r \times E_n \times [(t/0.2) \times (610x / D_x)]
\]

Where,
- \(E\) = Incident Energy in Joules/cm²
- \(C_r = 1.0\) for \(V > 1\) kV or \(1.5\) for \(V \leq 1\) kV
- \(E_n\) = the normalized incident energy (Joules/cm²), at the worker location for 24" (610mm) gap and 0.2 seconds
- \(t\) = arcing time in seconds from protective equipment Time Current Curves at \(I_a\) or 85% of \(I_a\) (whichever yields a longer clearing time)
- \(D\) = working distance in mm (inches * 25.4)
- \(X\) = distance exponent (for \(V = .208\) to 1 kV, \(X = 2.000\) for Open Air, \(X = 1.473\) for Switchgear)

\[E\) (calories/cm²) = \(E\) (Joules/cm²) * 0.24}
Example Calculations using the above formulas

3Ø Pad Transformer Characteristics
300 kVA, 12470GrdY/7200, 208Y/120, IZ = 2.0%, with Current Sensing Bayonet Fuse 353C10, arc in a box

Step 1  Estimation of the Arcing Short Circuit Current

\[ I_{LV \text{Rated}} = \frac{kVA}{LV\text{v}} / \sqrt{3} = \frac{300}{0.208} / 1.732 = 832.74 \text{ amperes} \]
\[ I_{bf} = \frac{I_{LV \text{Rated}}}{(%IZ / 100)} = \frac{832.74}{(2.0 / 100)} = 41.637 \text{ amperes} = 41.637 \text{ kA} \]
\[ k = -0.097 \text{ for arcs in a box} \]
\[ V = 0.208 \text{ kV} \]
\[ G = 25.4 \text{ mm (1")} \]

Using the equation for Arcing Short Circuit Current:

\[ \log I_a = k + 0.662 * \log I_{bf} + 0.0966 * V + 0.000526 * G + 0.5588 * V * \log I_{bf} - 0.00304 * G * \log I_{bf} \]

\[ \log I_a = -0.097 + 0.662 * \log 41.637 + 0.0966 * 0.208 + 0.000526 * 25.4 + 0.5588 * 0.208 * \log 41.637 - 0.00304 * 25.4 * \log 41.637 \]
\[ \log I_a = 1.07172 \]
\[ I_a = 10^{1.07172} = 11.80 \text{ kA} \]

Step 2  Calculation of the Normalized Incident Energy at Working Distance

Using the equation for Normalized Incident Energy at Working Distance:

\[ \log E_n = k_1 + k_2 + [1.081 * (\log I_a)] + 0.0011 * G \]
\[ \text{where,} \quad k_1 = -0.555 \text{ for arcs in a box} \]
\[ k_2 = -0.113 \text{ for grounded} \]

\[ \log E_n = -0.555 - 0.113 + [1.081 * (\log 11.80)] + 0.0011 * 25.4 \]
\[ \log E_n = 0.51847 \]
\[ E_n = 10^{0.51847} = 3.30 \text{ Joules/cm}^2 = 0.79 \text{ calories/cm}^2 \]

Step 3  Calculation of the Incident Energy at Other Working Distances and Other Fault Clearing Times

Using the equation for Incident Energy at Other Working Distance and Other Fault Clearing Times:

\[ E = 4.184 * C_f * E_n * [(t/0.2) * (610^x / D^y)] \]
\[ \text{where,} \quad C_f = 1.5 \text{ for } V \leq 1 \text{ kV} \]
\[ t = \text{Total Clearing time from the TCC's of the protective equipment, which this example is a 353C10 bayonet fuse at 85\% I_a (worst case)} \]
\[ x = 1.473 \text{ for } V = 0.208 \text{ to } 1 \text{ kV in Switchgear} \]
\[ D = \text{working distance in mm (18" * 25.4)} = 457.2 \text{ mm} \]

From above, \[ I_a (LV) = 11.80 \text{ kA} \]
\[ I_a (HV) = 11.80 * 208 / 12470 = .19682 \text{ kA} = 196.82 \text{ amperes} \]
\[ I_a (HV) \text{ worst case} = 196.82 * 0.85 = 167.30 \text{ amperes} \]

From TCC curve total clearing time for a 353C10 bayonet fuse, \( t = 0.550 \text{ seconds} \)

\[ E = 4.184 * 1.5 * 3.30 * [(0.560/0.2) * (610^{1.473} / 457.2^{1.473})] \]
\[ E = 88.68 \text{ Joules/cm}^2 = 21.280 \text{ calories/cm}^2 \]

Since the Incident Energy is greater than 8 cal/cm² and less than 25 cal/cm²:

Therefore, Category 3 PPE is required
Maximum Clear Time Current Characteristic Curves
Bay-O-Net Current (Fault) Sensing 3530 Fuse Links in Transformer Oil
Interesting Timing Comparison Between Arc Flash Events and Airbag Deployment

Arc Flash Event (from us.ferrazshawmut.com/arcflash/arc_background/hazards.cfm):

0  Time = 0.000 seconds (0 cycles)
   ▶ Available fault current is 23kA.
   ▶ Clearing time of circuit breaker is set at 6 cycles (0.1 seconds)

1  Time = 0.0002 seconds (0.012 cycles)
   ▶ Massive quantity of power is delivered to the conductor
   ▶ Rapid heating quickly takes the copper wire past its melting and boiling points
   ▶ As the circuit through the shorting conductor is broken, an arc is established between the electrodes
   ▶ Brilliant light begins to emanate from the arc

2  Time = 0.0007 seconds (0.042 cycles)
   ▶ Current flowing through highly ionized air converts electrical energy into massive amounts of heat energy, causing plasma cloud to expand outward, away from the electrodes
   ▶ Massive quantity - megawatts - of power delivered to the arc begins to increase
   ▶ Surrounding air undergoes ultra-rapid heating, but cannot expand fast enough to accommodate the extreme increase in heat energy; pressure begins to build
   ▶ Arc burns in a mixture of air and copper vapor from the electrodes
   ▶ Plasma jets begin to form, driven by increasing magnetic forces
   ▶ Light brilliance is well above eye-damaging levels

3  Time = 0.0020 seconds (0.120 cycles)
   ▶ Current continues to flow through the plasma cloud, converting additional electrical energy into massive amounts of heat energy
   ▶ Plasma is initially forced downward from the electrodes by magnetic forces and the plasma jets
   ▶ Expansion of the heated air and vaporized copper, which is 67,000 times its solid volume, accelerates away from the arc at speeds nearing the speed of sound
   ▶ Molten metal from the electrodes is ejected into the plasma jets at the electrode tips
4  Time = 0.0032 seconds (0.192 cycles)
   ▶ Sustained current flow through plasma continues to convert electrical energy into massive amounts of heat energy
   ▶ With continued heating, plasma continues to expand away from the arc to the front of the test box, and is driven downward from electrodes by the plasma jets
   ▶ Molten metal from electrodes continues to be ejected into plasma jets
   ▶ Light brilliance still well above eye-damaging levels

5  Time = 0.0051 seconds (0.306 cycles)
   ▶ Sustained current flow through the plasma continues to convert electrical energy into massive amounts of heat energy
   ▶ Plasma is initially forced downward from the electrodes by the growing plasma jets
   ▶ Continued heating of plasma causes it to expand beyond the test box
   ▶ Both sides of the box are visibly distended by the increasing pressure
   ▶ Molten metal from the electrodes continues to be ejected at high velocity into the plasma jets; some will exit the box with the explosive expansion of air
   ▶ Light brilliance still well above eye-damaging levels

6  Time = 0.0085 seconds (0.510 cycles)
   ▶ First half-cycle of fault is complete
   ▶ Sustained current flow through plasma cloud continues to convert electrical energy into massive amounts of heat energy
   ▶ Plasma has expanded beyond test box
   ▶ More molten metal from electrodes is being ejected into the plasma jets
   ▶ Light brilliance still well above eye-damaging levels

7  Time = 0.0167 seconds (1.002 cycles)
   ▶ First electrical cycle is complete
   ▶ Cooling copper ions combine with oxygen to form copper oxide “dust”, which appears as brownish smoke; other toxic gases are formed in similar fashion
   ▶ Sustained current flow continues to convert electrical energy into massive amounts of heat energy
   ▶ More molten metal is being ejected into plasma jets
   ▶ Shrapnel from the explosive force of the arc is hurled outward at high velocity
   ▶ Light brilliance still well above eye-damaging levels

8  Time = 0.0334 seconds (2.004 cycles)
   ▶ Second electrical cycle is complete
   ▶ Sustained current flow continues to convert electrical energy into massive amounts of heat energy
   ▶ Plasma still beyond test box
   ▶ More copper oxide dust and other toxic gases are visible
   ▶ More molten metal is being ejected into plasma jets
   ▶ Light brilliance still well above eye-damaging levels

9  Time = 0.0504 seconds (3.024 cycles)
   ▶ Third electrical cycle is complete
   ▶ Sustained current flow continues to convert electrical energy into massive amounts of heat energy
   ▶ Copper oxide dust and other toxic gases obscures view of calorimeter and box interior
   ▶ Plasma in text box still visible
   ▶ More molten metal being ejected into plasma jets
   ▶ Light brilliance still above eye-damaging levels

10 Time = 0.1015 seconds (6.090 cycles)
   ▶ Test lab circuit breaker opens
   ▶ Interruption of current flow stops conversion of electrical energy to heat energy; plasma begins to cool
   ▶ Remaining toxic gases are forced outward
   ▶ Remaining molten metal being ejected into plasma jets
Air Bag Deployment Events from (en.wikipedia.org/wiki/Airbag):

1. 15-30 ms – The decision to deploy an airbag in a frontal crash is made
2. <2 ms – After the decision to deploy is made the electric match activates
3. 20-30 ms – After the electric match activates, the burning propellant generates inert gas which rapidly inflates the airbag
4. 60-80 ms – After the first moment of vehicle contact, both driver and passenger airbags are fully inflated

Final Observations:

Arc Flash Event
- **Amount of heat energy accumulated at front of box exceeded 6 cal/cm².** Heat incident on measuring devices at 18” working distance indicated heat levels capable of causing third burns on exposed flesh and igniting conventional clothing
- **Impulse sound levels were above OSHA’s 140 dB limit.** Without protection, permanent hearing impairment would be expected
- **Light levels were intense enough to cause immediate vision impairment** and increased chance of future cataract development
- **Toxic gases,** such as copper oxide dust, were forced out of enclosure
- **Shrapnel** was ejected at high velocities
- **Molten metal projectiles** contained enough heat to ignite conventional clothing

Airbag Deployment
- Although it is known that airbags activate very quickly, the speed of airbag deployment is relatively slow compared to arc flash events. Arc flash events are virtually over by the time it takes airbags just to decide when to deploy.